

Spectral/timing evolution of black-hole binaries

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Abstract. I briefly outline the state-paradigm that has emerged from the study of black-hole binaries with RossiXTE. This is the starting point of a number of studies that address the connection between accretion and jet ejection and the physical nature of the hard spectral components in these systems.

Keywords: Accretion and accretion disks – black hole binaries

PACS: 97.10.Gz, 04.25.dg

STATES AND STATE-TRANSITIONS

Almost fourteen years into the life of the RossiXTE mission (at the time of writing), the existing database of outbursts of transient black-hole binaries is very rich and constitutes a unique laboratory to understand accretion onto black holes. The dense coverage and high-flexibility of RossiXTE are indeed unique and not likely to be matched by new missions in the near future. A large amount of theoretical and observational work has focused on the hard and soft states, in particular regarding the energy spectrum (see e.g. Gilfanov 2009). In the hard state (LHS), the energy spectrum shows a clear high-energy cutoff around $\sim 50\text{--}100$ keV, while in the soft state (HSS) a cutoff was not observed up to ~ 1 MeV (Grove et al. 1998). These spectra are interpreted as the result of Comptonization from a combination of thermal and non-thermal electrons (see e.g. Ibragimov et al. 2005). Different theoretical models differ in the details of the physical location and combination of these components.

However, a more dynamic view of the time evolution of the outbursts of these objects is now possible. From this, it is possible to identify a small number of states, which in addition to the hard and soft ones, include intermediate states. These are relatively short-lived and mark transitions between hard and soft and vice-versa. Their importance lies in a number of aspects. First, the study of the transition between two very different states as the hard and soft state, which are characterized by qualitatively different energy spectra, provides the best opportunity to establish their nature. In simple words: if the transition is between a thermal or hybrid Comptonization spectrum and a non-thermal spectrum, what happens in between? Second, it has been shown that some of these transitions correspond to changes in the infrared/radio emission (see e.g. Homan et al. 2005; Coriat et al. 2009) or to the ejection of relativistic jets (Fender, Belloni & Gallo 2004; Fender, Homan & Belloni 2009; Fender 2009; Gallo 2009).

The basic tools used for RossiXTE data for approaching the evolution of the X-ray emission of transient black hole binaries in outburst are the Hardness-Intensity Diagram (HID), where the total count rate is plotted as a function of hardness and the Hardness-Rms Diagram (HRD), where the fractional rms, integrated over a broad

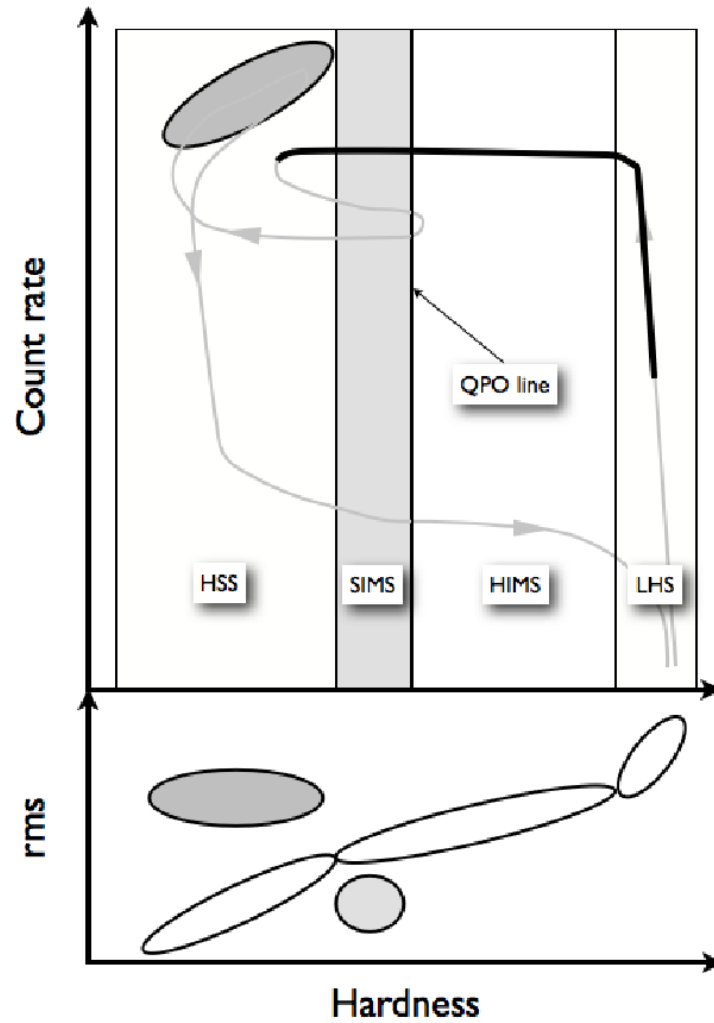


FIGURE 1. Top panel: sketch of the main regions of the Hardness-Intensity Diagram, corresponding to different sources states as identified through variability parameters. The path is an example of outburst evolution. The black segment of the path corresponds to the interval covered by GX 339–4 in 2006 (see Motta, Homan & Belloni 2009) and Fig. 2. For the definition of QPO line, see text.

range of frequencies, is plotted versus hardness. Both diagrams are produced with X-ray photons in the approximate 3–20 keV range. You can see several examples in Belloni et al. (2005), Homan & Belloni (2005), Fender, Homan & Belloni (2009), Belloni (2009), Dunn et al. (2009). A schematic picture with the typical path of an outburst and the states and state transitions is shown in Fig. 1. The four states are Low/Hard (LHS), Hard-Intermediate (HIMS), Soft-Intermediate (SIMS) and High-Soft (HSS) (adapted from Belloni 2009). The vertical lines mark the state transitions.

State transitions are sharp: although obviously the 3–20 keV energy spectrum cannot be much different when crossing the vertical lines, detailed analysis of the properties of fast aperiodic variability shows that indeed marked changes take place there (see Belloni 2009). Therefore, the position of the transition lines is not at all arbitrary, but is

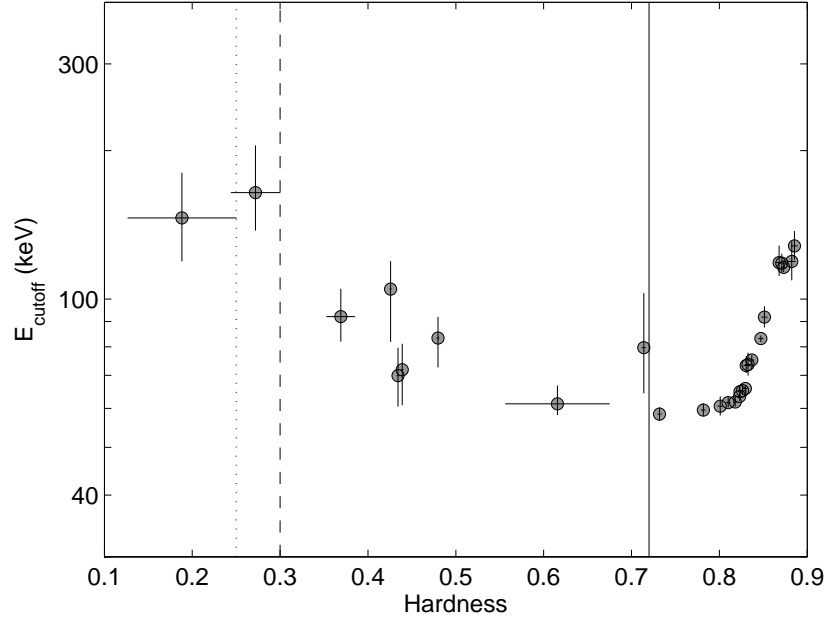


FIGURE 2. High-energy cutoff as a function of spectral hardness for the 2006 data of GX 339–4 (see Motta et al. 2009). The lines mark state transitions (thick: LHS-HIMS; dashed: HIMS-SIMS, the QPO-line; dotted: HIMS-SIMS).

fixed by observations. Particularly important is the transition between HIMS and SIMS, marked as QPO line in Fig. 1 as it involves the appearance of a particular Quasi-Periodic Oscillation associated with the SIMS (see Belloni 2009; Casella, Belloni & Stella 2005).

CONNECTION TO JET EJECTION

In the past few years, thanks to an increased observational radio/X-ray activity, a picture of the connection between accretion and ejection is also emerging (see Fender 2009; Gallo 2009). In particular, it is now clear that while the LHS is associated to compact radio jets and the HSS to quenched radio emission, the major jet ejections take place during intermediate states. Fender, Belloni & Gallo (2004) identified the QPO-line with the position corresponding to the ejection of fast jets (the “Jet-line”). However, recently Fender, Homan & Belloni (2009) found that this association is not perfect nor causal: the two lines are crossed within a couple of weeks from each other, in either sequence.

HIGH-ENERGY COMPONENTS

Although across transitions the energy spectrum does not change appreciably, once energies above 20 keV are considered the picture changes. In particular, recent results on GX 339–4 have shown that the high-energy cutoff of the hard spectral component

changes in non-monotonic way across the transition (Motta et al. 2009). Figure 2 shows the evolution of this parameter as a function of hardness, over the path sketched in black in Fig. 1. in the LHS, the high-energy cutoff decreases from 120 to 60 keV as the sources brightens (and softens), then the trend is reversed and in the HIMS there is a marked increase back to ~ 100 keV. After the QPO-line, the cutoff energy is high, possibly not detected significantly (see also Motta et al., this volume). This evolution is rather complex. Although the LHS behaviour is simple to understand, as the simultaneous increased soft emission cools the electrons responsible for the Comptonization. However, the trend reversal is still puzzling. The same behaviour was shown by other sources (see e.g. Joinet et al. 2008; Motta et al. 2009).

CONCLUSIONS

We now have a clear phenomenological picture of the evolution of black-hole transients, which can be compared to that of neutron-star binaries and active galactic nuclei (see Belloni 2009). It is clear that state-transitions hold the key to a deeper understanding. Although they are transient and difficult to observe, the data already existing show that the spectral evolution is complex and still needs to be understood.

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